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13. ABSTRACT (Maximum 200 words) A methodology for designing compliant mechanisms for a given static shape change task has been developed. In this methodology, given two different shapes the synthesis program automatically generates the form (topology, size and shape) of an optimized compliant mechanism which is actuated by minimum number of actuators (typically one). The energy from the actuator is transferred via compliant mechanism to deform one given shape into another desired shape. The basic premise is to distribute the actuation energy of remote actuator via compliant transmission (distributed compliance) instead of using a plethora of actuators (distributed actuation systems).			
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SHAPE CONTROL OF ADAPTIVE STRUCTURES USING COMPLIANT MECHANISMS

AFOSR GRANT NUMBER F49620-96-1-0205

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1.0 Objective:

We have developed a methodology for designing compliant mechanisms for a given static shape change task. In this methodology, given two different shapes the synthesis program automatically generates the form (topology, size and shape) of an optimized compliant mechanism which is actuated by minimum number of actuators (typically one). The energy from the actuator is transferred via compliant mechanism to deform one given shape into another desired shape. The basic premise is to distribute the actuation energy of remote actuator via compliant transmission (distributed compliance) instead of using a plethora of actuators (distributed actuation systems).

The static shape change concept is illustrated here in the context of the leading edge and trailing edge of an airfoil as depicted in Figure below. The PI (Kota) originally developed this concept in 1994. A systematic methodology for static shape control was developed under the AFOSR contract.

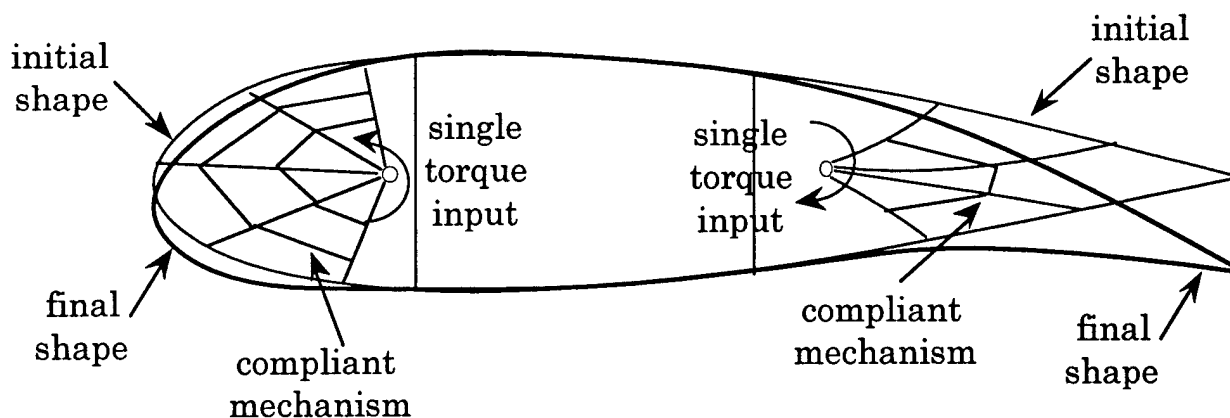


Figure 1: Adaptive shape change of LE and TE using embedded compliant mechanisms.

2.0 Relation to AFOSR

Currently, considerable research is directed towards the application of smart structure technologies to the active control of vibration, flutter and shape of fixed-wing as well as rotary-

wing of aircraft. Although, the application of this new technology has shown promising results, its transition to full-scale aircraft is impeded by several challenges. Key barriers are

1. the stroke length of the smart actuators, and
2. complexity associated with the distributed actuation.

Although the shape control of a smart structure essentially involves controlled deformation of the structure, *flexibility of the underlying structure* is overlooked in the design of smart structures.

Rather than employing a plethora of actuators to locally deform an otherwise stiff structure, an alternative approach is to draw energy from a few remotely located actuators and distribute the energy to the structure through some intermediary mechanism. An efficient agent for such a transformation of energy from the source to the structure is strain energy, and the mechanism that most conveniently furnishes this agent is a compliant mechanism. A compliant mechanism being a "structure with controlled mobility", it is well suited for controlling the deformation of a structural member.

3.0 Basic Research Issues

- 2.0 identify the minimal number and "optimal" locations (on the member undergoing shape change) of output points of the compliant mechanism,
- 3.0 establish a topology for the mechanism,
- 4.0 determine the dimensions of all of the segments of the mechanism, and
- 5.0 determine the location(s) and the magnitude(s) of the input actuation(s).

Assumptions: (i) the deflections are *small* in order for the linear beam theory to be valid, (ii) the structure is *slender* so that axial and shear strains are negligible.

4.0 Approach

A brief overview of the design methodology is given below. A detailed description of the static shape change method is described in [Saggere and Kota 1999] and a detail account for size and geometry optimization can be found in [Hetrick and Kota 1999].

4.1 Problem Statement

Given: Two or more shapes (airfoils), preferred region of the actuator, external loads to be sustained (air loads), space constraints (or packaging constraints) and material specification (wing skin, preferred material for the unknown compliant mechanism), acceptable error, and available actuation power (if known).

Determine: Design a compliant mechanism – determine the topology, size, cross-sectional shapes, and geometry of various segments

4.2 Design Procedure

STEP 1: Determine Topology

The topology is influenced by prescribed error tolerance and the geometric complexity of the desired shape change.

- Compute the strain energy change in the given structure as it undergoes desired shape change)
- Determine the number and location of points along the contour where moments need to be applied to produce the computed strain energy. Minimize the number of these points. These are the points where the compliant segments will be eventually attached.
- Create a framework of beam segments connecting the “output points” determined in step 2 to the yet to be located input actuation point.

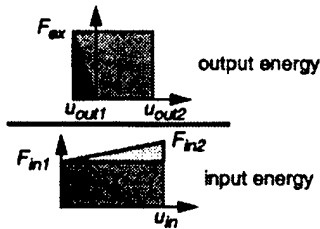
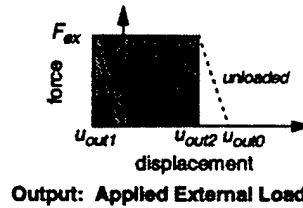
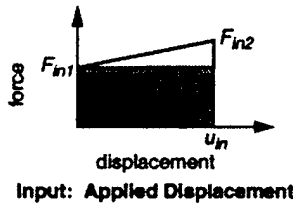
STEP 2: Determine major dimensions

- Determine suitable dimensions of various compliant segments as well as the specific location and magnitude of the input actuation
- Minimize the Least Square error between the desired and the achieved shape changes.
- The converged solution yields a set of values for all of the design variables viz. A_i , ϕ , and (X_o, Y_o) .

STEP 3: Maximize the energy efficiency of the mechanism

- Formulate an energy-efficiency scheme where, the design variables are the cross sectional areas of various compliant segments. The input (actuator) displacement is known and the external load F_{ex} (air load) is taken in consideration. The energy efficiency method is summarized below. Details are given in [Hetrick and Kota 1999].

Force-Displacement History



$$\eta_{efficiency} = \frac{F_{ex} \left(u_{out2} + \frac{1}{2} u_{out1} \right)}{\frac{u_{in}}{2} (F_{in1} + F_{in2})}$$

maximize $\eta_{\text{efficiency}(\text{sizing}_i, \text{geometry}_j)}$

subject to:

$$s_{i_{\min}} \leq s_i \leq s_{i_{\max}} \quad \text{and} \quad g_{j_{\min}} \leq g_j \leq g_{j_{\max}}$$

$$h_1 = \frac{F_{ex}}{F_{in1}} - MA_{\text{desired}} \quad \text{or} \quad h_1 = \frac{u_{out2}}{u_{in}} - GA_{\text{desired}}$$

$$g_1 \leq \int \text{Volume-Resource}_{\max}$$

$$g_{i+1} \leq \sigma_i - \sigma_{\max} \quad i = 1 \dots N \text{ elements}$$

where, s_i represent parametric sizing variables of the mechanism, g_i is the specified total volume (or weight) constraint, MA is the desired Mechanical Advantage (force amplification), GA is the desired Geometric Advantage (stroke amplification)
 σ_i is the stress constraint (material choice)

STEP 4: Repeat step 3 for each segment of the compliant mechanism topology. This establishes the exact geometry, and size of all segments and guarantees that the energy transmission efficiency is maximized.

5.0 Significant Results

Based on the methodology briefly outlined above, we have developed a mathematical synthesis procedure for designing embedded compliant mechanisms for a given static shape change application. The details of this procedure are published in AIAA journal [Saggere and Kota 1999]. This method, based on first principles of continuum mechanics and kinematics, automatically generates a feasible topology of a compliant mechanism that meets the prescribed static shape change specification. Once the topology is obtained we need to determine the exact size and shape of all elements (beam elements) of the compliant mechanism so that energy is efficiently transmitted from the actuator to the outer shape-change surface. A new energy-efficiency method was developed for optimizing the size and shape of the complaint mechanism. The size/shape synthesis [Hetrick and Kota 1999] method is a robust optimization scheme and was successfully tested on many design examples. One of applications of this method was the design of complaint MEMS multiplier that the PI has developed in collaboration with Sandia National Labs. The compliant mechanism optimized with this scheme amplifies the stroke of a MEMS electrostatic actuator 20 times with 75% energy efficiency. Integration of such a complaint transmission with the electrostatic actuator has increased the power density of the device one hundred times. The design has been recently fabricated and successfully tested (10^{10} cycles) by the Sandia Labs and two patent applications are currently pending.

6.0 Transition to Applications

Under a separate contract with WPAFB, the PI (S. Kota) has designed, fabricated and tested a 3-foot wing section of NACA63418 profile embedded with compliant mechanisms. The basic

concept is illustrated in Figure 2. Figure 3 shows the results from non-linear finite element analysis of the leading edge compliant mechanism designed to produce a 6-degree camber change using a single actuator.

Note that the original specification by WPAFB called for a 6-degree camber change. Using this approach (leading-change) camber changes much larger than 6-degrees can be realized. This technology offers many benefits to the Air Force including: (1) survivability characteristics, (2) improved stability and control, (3) optimized lift on cruise conditions, and (4) an integrated pre- and in-flight deicer.

The leading-edge compliant mechanism is designed to withstand the external air-loads. The mechanism has a very high mechanical advantage i.e., a relatively smaller input force can withstand large external forces. The choice of material and the form (topology, size and shape) of compliant mechanism depend on available actuation forces, external air loads, packaging requirements etc.

7.0 Future Directions

Development of an Integrated design methodology for systematically synthesizing compliant mechanisms under dynamic load specifications and non-linear deformation mode. This is primarily focussed on dynamic shape change application. The method will be ultimately validated using a realistic design example.

Development of a Design and Simulation software to simulate the dynamic performance of a wing embedded with compliant LE mechanisms, and actuators under the action of external air loads.

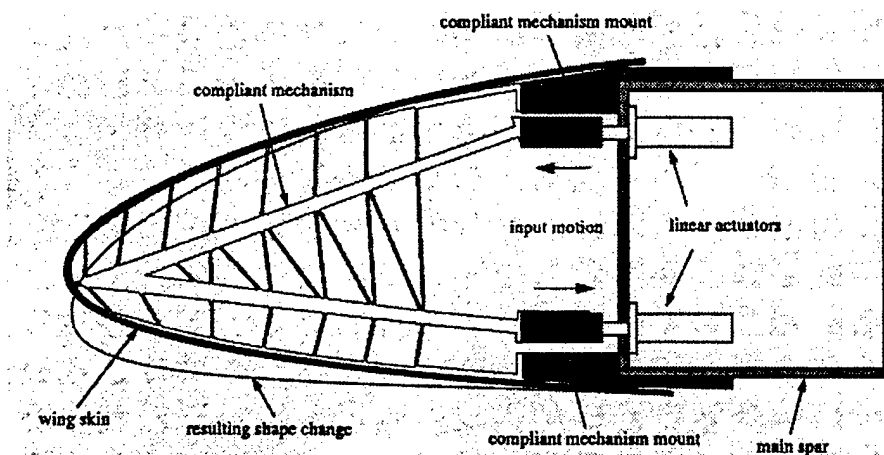


Figure 2: The Adaptive Compliant Wing Concept [Kota 1997]

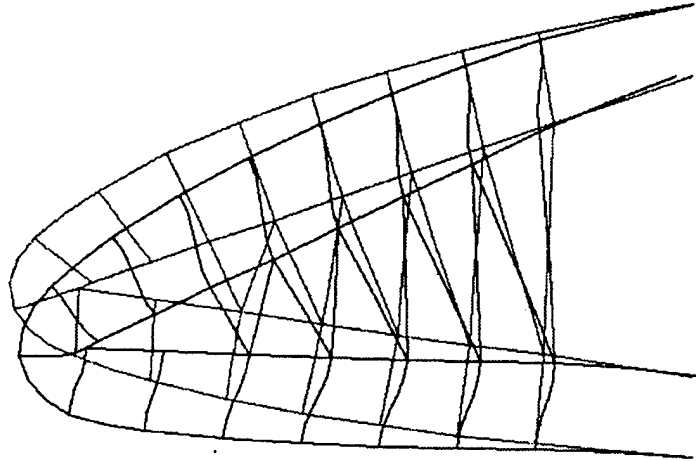


Figure 3: Non-linear finite element static analysis of the actual mechanism showing the 6-degree LE camber change of NACA 63418 profile under the action of input forces [Kota 1998]

8.0 Personnel:

Principal Investigator: Sridhar Kota, Associate Professor

Co-Investigator: Prof. Noboru Kikuchi

Research Associate: Dr. Zhe Li

Graduate Students:

Joel Hetrick: Developed the energy-efficiency algorithm for topology and size optimization of compliant mechanisms. Completed Ph.D. in August 1999. He is currently employed as an Assistant Professor at the University of Wisconsin-Madison. He was partially funded under the AFOSR contract.

Laxman Saggere: Developed mathematical procedures for designing compliant mechanisms for static shape change applications. Completed Ph.D. in December 1998. He is currently employed as a Research Associate at the Department of Aerospace Engineering at MIT. He was completely funded under the AFOSR contract.

Mary Frecker: Developed mathematical procedures for topological synthesis of compliant mechanisms using ground-truss approach. Completed Ph.D. in May 1997. She is currently employed as an Assistant Professor of Mechanical Engineering, Pennsylvania State University. She was partly funded under the AFOSR contract.

9.0 Publications:

9.1 Journal Publications (1999)

Hetrick J., Kota S., "An Energy Efficiency Formulation for Parametric Size and Shape Optimization of Compliant Mechanisms," *ASME Transactions, Journal of Mechanical Design*, June 1999, Vol. 21, pp. 229-234.

Saggere, L., Kota S., "Static Shape Control of Smart Structures Using Compliant Mechanisms," *AIAA Journal*, Volume 37, Number 5, pp.572-578, May 1999.

Frecker M., Kikuchi N., Kota S., "Topology Optimization of Compliant Mechanisms with Multiple Outputs," *Structural Optimization*, Springer-Verlag 1999.

Frecker M., Kikuchi N., Kota S., "Topology Optimization of Compliant Mechanisms with Multiple Outputs," *Structural Optimization*, Springer-Verlag 1999.

S. Kota, J. Hetrick, Z. Li, L. Saggere, "Tailoring Unconventional Actuators with Compliant Transmissions: Design Methods and Applications," – To appear in *ASME/IEEE Journal of Mechatronics*, December 1999.

J-Y Joo, S. Kota, and N. Kikuchi, "Optimal Topology Design of Compliant Mechanisms Using Frame Elements," *Mechanics and Structures of Machines* (in review)

9.2 Conference papers (1999)

Hetrick J., Kikuchi N., S. Kota, "Robustness of Compliant Mechanism Topology Optimization Formulations," *Proceedings of the SPIE International Symposium on Smart Structures and Materials – Mathematics and Control of Smart Structures*, March, Newport Beach, CA. March 1999

S. Kota, "Design of Compliant Mechanisms with Applications to MEMS and Smart Structures," *Tenth World Congress on the Theory of Machines and Mechanisms (IFTToMM)*, Oulu, Finland, June 1999.